Appendix D

CMOS Schmitt Trigger—A Uniquely Versatile Design Component

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INTRODUCTION

The Schmitt trigger has found many applications in numerous circuits, both analog and digital. The versatility of a TTL Schmitt is hampered by its narrow supply range, limited interface capability, low input impedance and unbalanced output characteristics. The Schmitt trigger could be built from discrete devices to satisfy a particular parameter, but this is a careful and sometimes time-consuming design.

The CMOS Schmitt trigger, which comes six to a package, uses CMOS characteristics to optimize design and advance into areas where TTL could not go. These areas include: interfacing with op amps and transmission lines, which operate from large split supplies, logic level conversion, linear operation, and special designs relying on a CMOS characteristic. The CMOS Schmitt trigger has the following advantages:

- High impedance input ($10^{12}\Omega$ typical)
- Balanced input and output characteristics
  - — Thresholds are typically symmetrical to ½ V_{CC}
  - — Outputs source and sink equal currents
  - — Outputs drive to supply rails
- Positive and negative-going thresholds show low variation with respect to temperature
- Wide supply range (3V–15V), split supplies possible
- Low power consumption, even during transitions
- High noise immunity, 0.70 V_{CC} typical

Applications demonstrating how each of these characteristics can become a design advantage will be given later in the application note.

ANALYZING THE CMOS SCHMITT

The input of the Schmitt trigger goes through a standard input protection and is tied to the gates of four stacked devices. The upper two are P-channel and the lower two are N-channel. Transistors P3 and N3 are operating in the source follower mode and introduce hysteresis by feeding back the output voltage, out', to two different points in the stack.

When the input is at 0V, transistors P1 and P2 are ON, and N1, N2 and P3 are OFF. Since out' is high, N3 is ON and acting as a source follower, the drain of N1, which is the source of N2, is at $V_{CC} - V_{TH}$. If the input voltage is ramped up to one threshold above ground transistor N1 begins to turn ON, N1 and N3 both being ON form a voltage divider network biasing the source of N2 at roughly half the supply. When the input is a threshold above ½ V_{CC}, N2 begins to turn ON and regenerative switching is about to take over. Any more voltage on the input causes out' to drop. When out' drops, the source of N3 follows its gate, which is out', the influence of N3 in the voltage divider with N1 rapidly diminishes, bringing out' down further yet. Meanwhile P3 has started to turn ON, its gate being brought low by the rapidly dropping out'. P3 turning ON brings the source of P2 low and turns P2 OFF. With P2 OFF, out' crashes down. The snapping action is due to greater than unity loop gain through the stack caused by positive feedback through the source follower transistors. When the input is brought low again an identical process occurs in the upper portion of the stack and the snapping action takes place when the lower threshold is reached.

Out' is fed into the inverter formed by P4 and N4; another inverter built with very small devices, P5 and N5, forms a latch which stabilizes out'. The output is an inverting buffer capable of sinking 360 μA or two LPTTL loads.

The typical transfer characteristics are shown in *Figure 2*; the guaranteed trip point range is shown in *Figure 3*.

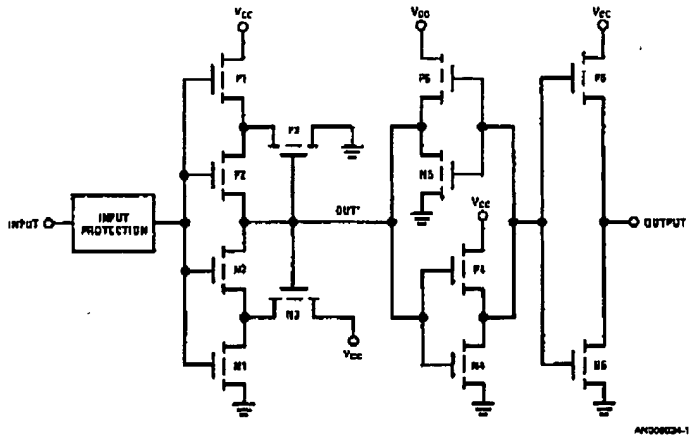


FIGURE 1. CMOS Schmitt Trigger

WHAT HYSTERESIS CAN DO FOR YOU

Hysteresis is the difference in response due to the direction of input change. A noisy signal that traverses the threshold of a comparator can cause multiple transitions at the output, if the response time of the comparator is less than the time between spurious effects. A Schmitt trigger has two thresholds: any spurious effects must be greater than the threshold difference to cause multiple transitions. With a CMOS Schmitt at V_{CC} = 10V there is typically 3.6V of threshold difference, enough hysteresis to overcome almost any spurious signal on the input.

A comparator is often used to recover information sent down an unbalanced transmission line. The threshold of the comparator is placed at one half the signal amplitude (See *Figure 4b*). This is done to prevent slicing level distortion. If a 4 μs wide signal is sent down a transmission line a 4 μs wide signal should be received or signal distortion occurs. If the comparator has a threshold above half the signal amplitude, then positive pulses sent are shorter and negative pulses are lengthened (See *Figure 4c*). This is called slicing level distortion. The Schmitt trigger does have a positive offset, V_{T+}, but it also has a negative offset V_{T-}. In CMOS these offsets are approximately symmetrical to half the signal level so a 4 μs wide pulse sent is also recovered (see *Figure 4d*). The recovered pulse is delayed in time but the length is not changed, so noise immunity is achieved and signal distortion is not introduced because of threshold offsets.

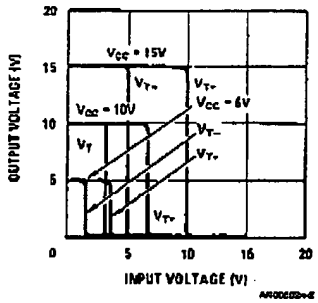


FIGURE 2. Typical CMOS Transfer Characteristics for Three Different Supply Voltages

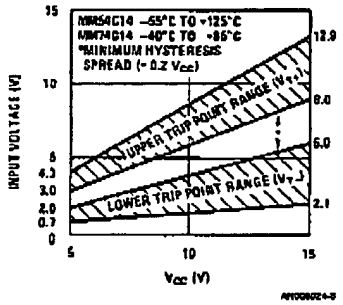


FIGURE 3. Guaranteed Trip Point Range

Schmitt Trigger

Introduction

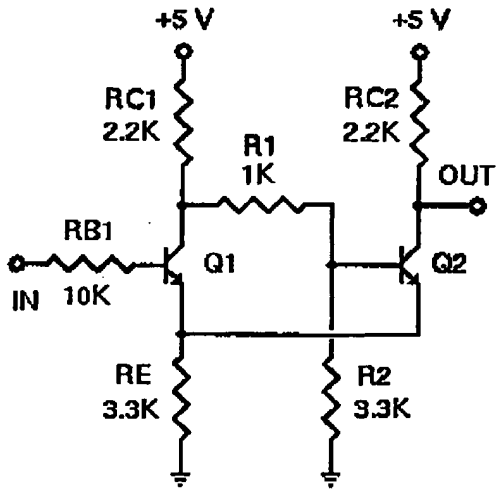
Sometimes an input signal to a digital circuit doesn't directly fit the description of a digital signal. For various reasons it may have slow rise and/or fall times, or may have acquired some noise that could be sensed by further circuitry. It may even be an analog signal whose frequency we want to measure. All of these conditions, and many others, require a specialized circuit that will "clean up" a signal and force it to true digital shape.

The required circuit is called a *Schmitt Trigger*. It has two possible states just like other multivibrators. However, the trigger for this circuit to change states is the input voltage level, rather than a digital pulse. That is, the output state depends on the input level, and will change only as the input crosses a pre-defined threshold.

In this experiment, we will look at the theory of this circuit's operation, and then build one to demonstrate its real-world operation.

Schematic Diagram

Unlike the other multivibrators you have built and demonstrated, the Schmitt Trigger makes its feedback connection through the emitters of the transistors as shown in the schematic diagram to the right. This makes for some useful possibilities, as we will see during our discussion of the operating theory of this circuit.



To understand how this circuit works, assume that the input starts at ground, or 0 volts. Transistor Q1 is necessarily turned off, and has no effect on this circuit. Therefore, RC1, R1, and R2 form a voltage divider across the 5 volt power supply to set the base voltage of Q2 to a value of $(5 \times R2)/(RC1 + R1 + R2)$. If we assume that the two transistors are essentially identical, then as long as the input voltage remains significantly less than the base voltage of Q2, Q1 will remain off and the circuit operation will not change.

Note: Classical analyses of this circuit include the forward current gain, h_{FE}, of the two transistors. This was important in the early days of transistors when a signal transistor was doing well to have a current gain of 30. Modern transistors have a much higher gain (160 for the 2N3904/2N3906, 200 for the 2N4124/2N4126), so they don't have the same limitations as older transistors. We can ignore the effects of transistor base current, although we do still need to account for V_{BE} for the two transistors.

While Q1 is off, Q2 is on. Its emitter and collector current are essentially the same, and are set by the value of RE and the emitter voltage, which will be less than the Q2 base voltage by V_{BE}. If Q2 is in saturation under these circumstances, the output voltage will be within a fraction of the threshold voltage set by RC1, R1, and R2. It is important to note that the output voltage of this circuit cannot drop to zero volts, and generally not to a valid logic 0. We can deal with that, but we must recognize this fact.

Now, suppose that the input voltage rises, and continues to rise until it approaches the threshold voltage on Q2's base. At this point, Q1 begins to conduct. Since it now carries some collector current, the current through RC1 increases and the voltage at the collector of Q1 decreases. But this also affects our voltage divider, reducing the base voltage on Q2. But since Q1 is now conducting it carries some of the current flowing through RE, and the voltage across RE doesn't change as rapidly. Therefore, Q2 turns off and the output voltage rises to +5 volts. The circuit has just changed states.

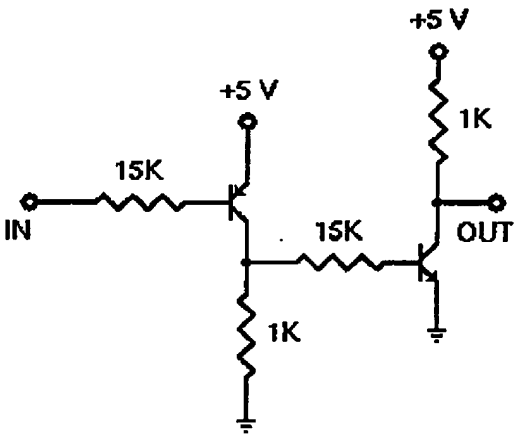
If the input voltage rises further, it will simply keep Q1 turned on and Q2 turned off. However, if the input voltage starts to fall back towards zero, there must clearly be a point at which this circuit will reset itself. The question is, What is the falling threshold voltage? It will be the voltage at which Q1's base becomes more negative than Q2's base, so that Q2 will begin conducting again. However, it isn't the same as the rising threshold voltage, since Q1 is currently affecting the behavior of the voltage divider.

We won't go through all of the derivation here, but when V_{IN} becomes equal to Q2's base voltage, Q2's base voltage will be:

$$V_{B2} = \frac{5 + V_{BE}\dfrac{RC2}{RE}}{1 + \dfrac{RC1}{RE} + \dfrac{RC1 + R1}{R2}}$$

As V_{IN} approaches this value, Q2 begins to conduct, taking emitter current away from Q1. This reduces the current through RC1 which raises Q2's base voltage further, increasing Q2's forward bias and decreasing Q1's forward bias. This in turn will turn off Q1, and the circuit will switch back to its original state.

Three factors must be recognized in the Schmitt Trigger. First, the circuit will change states as V_{IN} *approaches* V_{B2}, not when the two voltages are equal. Therefore V_{B2} is very close to the threshold voltage, but is not precisely equal to it. For example, for the component values shown above, V_{B2} will be 2.54 volts when Q1 is held off, and 2.06 volts as V_{IN} is falling towards this value.



Second, since the common emitter connection is part of the feedback system in this circuit, RE must be large enough to provide the requisite amount of feedback, without becoming so large as to starve the circuit of needed current. If RE is out of range, the circuit will not operate properly, and may not operate as anything more than a high-gain amplifier over a narrow input voltage range, instead of switching states.

The third factor is the fact that the output voltage cannot switch over logic levels, because the transistor emitters are not grounded. If a logic-level output is required, which is usually the case, we can use a circuit such as the one shown here to correct this problem. This circuit is basically two RTL inverters, except that one uses a PNP transistor. This works because when Q2 above is turned off, it will hold a PNP inverter off, but when it is on, its output will turn the PNP transistor on. The NPN transistor here is a second inverter to re-invert the signal and to restore it to active pull-down in common with all of our other logic circuits.

The circuit you will construct for this experiment includes both of the circuits shown here, so that you can monitor the response of the Schmitt trigger with L0.

The Trimmer Potentiometer

A new component that you will need for this project is a trimmer potentiometer. A *potentiometer* consists of a resistive element with a movable electrical contact touching it. This permits the potentiometer to serve as a continuously-variable voltage divider.

The figure to the right shows one of the many kinds of potentiometers available for a wide range of applications. This one uses a screw to slowly advance the moving contact along the resistance element. This allows accurate placement of the contact and reduces the likelihood that an accident may move the contact away from the desired position. The particular potentiometer that we will use requires 15 turns of the screw to cover the entire resistance range.

This particular type of potentiometer is typically known as a *trimmer potentiometer* (or *trimpot* for short), because it is intended to be adjusted or "trimmed" to a particular setting, and then left there to retain its setting. It will seldom need to be readjusted in normal use.

Parts List

To construct and test the Schmitt Trigger circuit on your breadboard, you will need the following